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MEASUREMENT AND INTERPRETATION OF CRUSTAL DEFORMATION RATES ASSOCIATED WITH POSTGLACIAL REBOUND

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I. Introduction

This project involves obtaining GPS measurements in Scandinavia, and using the measurements to estimate the viscosity profile of the Earth's mantle and to correct tide-gauge measurements for the rebound effect. Below, we report on several aspects of this project.

II. GPS Measurements

The permanent network set up by Onsala Space Observatory continues to operate, and the data are continuously being analyzed. The expanded DSGS was last occupied during the latter half of August, 1994. We are currently planning the Summer Campaign, to take place in August, 1995. J.L. Davis, the P.I., will travel to Sweden early summer 1995 to plan these measurements and to prepare for publication several papers describing the GPS measurements from the last several years.

At the Fall 1994 AGU meeting, we presented our analysis of one year of the continuous Fennoscandian network. This analysis (see the figure in Appendix A, which was one of the panels presented at the AGU meeting) represents the first detection of postglacial uplift by GPS.

III. Analysis of Tide-gauge Data

We have investigated the anomalous geographical variations in sea-level rates which have been reported for the east coast of North America. These rates, obtained from tide-gauge observations, must be corrected for glacial isostatic adjustment in order to estimate global sea-level change. For the first time, we invert tide-gauge observations to *solve* for corrections to the Earth model used to calculate the adjustment corrections. This inversion yields a significant correction to the lower-mantle viscosity. The corrected sea-level rates also exhibit significantly less geographic variability, and yield an estimate for sea-level rise much more in accordance with estimates from other areas on the Earth. Thus, in this paper we simultaneously (i) demonstrate a new procedure for obtaining information of Earth structure from tide-gauge data, (ii) use the procedure to obtain a new estimate of lower mantle viscosity (and demonstrate why with this data set we are most sensitive to this particular parameter), (iii) demonstrate that the new estimate of lower-mantle viscosity reduces significantly the geographic variability of the corrected sea-level rates, and (iv) provide a new estimate of sea-level rise for the eastern North American tide-gauge data set. We have submitted a paper to *Science* reporting these results (Appendix B).

IV. Relevant Publications

Mitrovica, J. X., J. L. Davis, and I. I. Shapiro, A spectral formalism for computing three-dimensional deformations due to surface loads, 1. Theory, *J. Geophys. Res.*, *99*, 7057–7074, 1994.

Mitrovica, J. X., J. L. Davis, and I. I. Shapiro, A spectral formalism for computing three-dimensional deformations due to surface loads, 2. Present-day glacial isostatic adjustment, *J. Geophys. Res.*, *99*, 7075–7102, 1994.

Mitrovica, J. X., and J. L. Davis, Some comments on the 3-D impulse response of a Maxwell viscoelastic Earth, *Geophys. J. Int.*, *120*, 227–234, 1995.

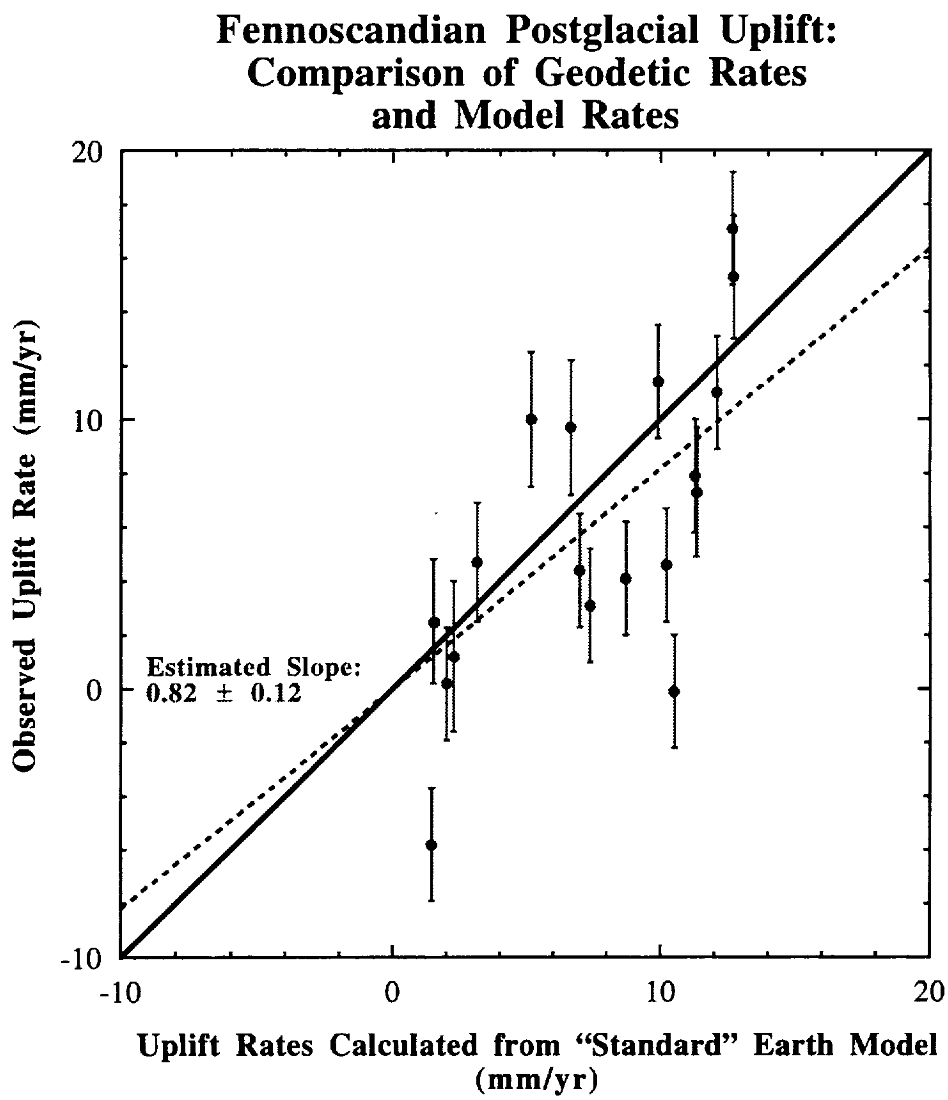
Elósegui, P., J. L. Davis, R. K. Jaldehag, J. M. Johansson, A. E. Niell, and I. I. Shapiro, Geodesy using the Global Positioning System: The effects of signal scattering on estimates of site position, in press, *J. Geophys. Res.*

Mitrovica, J. X., and J. L. Davis, The influence of a glaciation phase on predictions of post-glacial isostatic adjustment, submitted, *Earth Plan. Sci. Lett.*

Davis, J. L., and J. X. Mitrovica, Sea level rise, mantle viscosity, and the anomalous tide gauge record of eastern North America, submitted, *Science*.

Davis, J. L., J. X. Mitrovica, H.-G. Scherneck, N. W. Casey-McCabe, Investigation of Fennoscandian postglacial land uplift and Earth rheology using modern sea-level records, in preparation.

Appendix A. Figure presented at 1994 Fall AGU Meeting comparing Observed and Predicted Uplift Rates in Fennoscandia



Appendix B. Davis and Mitrovica, submitted.

Sea Level Rise, Mantle Viscosity, and the Anomalous

Tide Gauge Record of Eastern North America

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Anomalies in estimates of sea-level rise obtained from tide gauge records on the east coast of North America suggest the presence of errors in the Earth and/or ice models used to calculate corrections for glacial isostatic adjustment. The corrections are found to be highly sensitive to the lower-mantle viscosity, a consequence of the locations of the tide gauges relative to the "peripheral bulge" associated with the adjustment. In an inversion of the tide gauge data, a value of $(4.7 \pm 0.3) \times 10^{21}$ Pa s is obtained for the lower-mantle viscosity; this value reduces by a factor of $\sim$3 the variations in the corrected rates. A common sea-level rise for the period 1897–1988 of 1.4 ± 0.3 mm yr^{-1} is simultaneously estimated.

Present-day sea-level variations, as recorded by the global network of tide gauges, represent a rich data set for studying a wide range of natural and anthropogenic phenomena. Recent efforts (*1–3*) to estimate the rate of secular sea-level change using such data have addressed "correcting" the sea-level records for ongoing glacial isostatic adjustment, or GIA (*4*). The correction procedure, which involves the prediction of sea-level change associated with ice mass fluctuations on a (viscoelastic) Earth model, has been shown to improve the consistency (at least globally) of the rate estimates (*1–3*) from different tide gauge sites. The first such analyses (*1*) involved tide gauge records from 40 sites and suggested a globally coherent rise in sea-level at a rate of 2.4 ± 0.9 mm yr^{-1}. Applying a stricter criteria for tide gauge selection, which, for example, avoids records in regions of converging tectonic plates, has resulted in a revised estimate of 1.8 ± 0.1 mm yr^{-1} (*2*, *3*).

A significant proportion (~40%) of the tide gauge records used in the these estimates were associated with sites on the east coast of North America (Fig. 1). However, an examination of the raw and GIA-corrected sea-level rates (Fig. 2A, B) from this region indicated some unexplained and significant inconsistencies (*2*, *3*). The GIA corrections (*5*) were based on the ICE-3G model for the space-time history of the last deglaciation event (*6*) and an Earth model (henceforth the "standard" model) characterized by a factor of two jump in viscosity across the interface between the upper and lower mantle (*7*). The GIA-corrected sea-level rates (Fig. 1B) are clearly not coherent. This variation was characterized (*2*) as a "step" of about 1 mm yr^{-1}, from ~1.5 mm yr^{-1} for sites north of 38° to ~2.5 mm yr^{-1} for sites south of 38°.

The number of tide gauge records used to analyze global sea-level change is usually a small fraction of the total number available (*1*, *2*), because investigators generally limit their data set to those few sea-level records with a long timespan (50 years for Fig. 2A, for example). Sea level rates are determined by fitting a straight line to each independent tide gauge series, but interannual (including interdecadal) fluctuations in sea-level may be large. Limiting the data set to long time series is thus thought to reduce the effects of interannual fluctuations. Recently, a method for simultaneously analyzing rates for a given set of sites has been developed which takes advantage of the correlation of interannual variations for different sites (*8*). Because the interannual variations of sea-level are more accurately accounted for, and the correlations between the rate estimates are rigorously estimated, shorter time series of sea-level can be used. In applying this technique to the tide gauges on the east coast of North America (*9*), we used criteria (*10*) which limited the data set to 38 sea-level records. The north-south trend in the estimated rates is still apparent (Fig. 2C, D), but the variation appears to manifest itself not so much as a "step" but as a continuous decrease in rates north of $\sim 35°$. In any event, the process of correcting the tide gauge record from the east coast of North America for GIA using this specific combination of ice history and Earth model actually results in an increase in the scatter of the estimated sea-level rates.

The systematic variations in the GIA-corrected sea-level rates strongly suggest that the predicted GIA signal may, as a result of errors in the ice and/or Earth models, be inadequate. It has been suggested, for example, that a model with a thicker lithosphere may be more appropriate for this region (*1*, *3*), but we have found that such a model does not remove the anomalous variations in the corrected rates (*11*). This issue highlights the lack of consensus in the geophysical literature regarding not only the thickness of the Earth's lithosphere, but also the depth-dependence of mantle viscosity (*12–14*). Notwithstanding the potentially important influence of lateral heterogeneity in mantle rheology, previous inferences of viscosity at any particular depth can vary by as much as an order of magnitude. It has not, however, been determined whether reasonable modifications to the Earth model used in the GIA correction may remove the anomalous sea-level rate variations. It has, though, been suggested that the tide gauge data themselves may be used to determine these modifications (*3*).

To explore this approach, we have performed an iterative least-squares inversion in which the estimated sea-level rates were taken as the observables, and parameters were estimated representing adjustments to the lithospheric thickness, the viscosity of the upper mantle, and the viscosity of the lower mantle. A common sea-level rate was also estimated. Sensitivities (partial derivatives) were determined numerically using sea-level rates calculated for different parameter values. Our initial solutions clearly indicated that the sea-level rates favored an increase of a factor of $\sim$2 in the lower mantle viscosity. Furthermore, the formal uncertainty for this parameter was fairly small, indicating a sensitivity of the model to its value. Adjustments to the other two Earth model parameters were small, and therefore had relatively little effect on the predicted sea-level rates (*11*).

To understand the sensitivity of the predicted sea-level rates to the lower-mantle viscosity, it is necessary to understand aspects of the GIA phenomenon in eastern

North America. The present-day rate of sea-level change as predicted by the standard model (Fig. 3A) is characterized by a rapid sea-level fall to the northwest, associated roughly with the location of the ancient Laurentide ice sheet, and a moderate (0–3 mm yr^{-1}) sea-level rise in the "peripheral bulge" area to the south and west (*15*). The standard model predicts that the east coast of North America lies exclusively within the peripheral bulge region. Moving north from Florida along this coast the predicted sea-level rise increases monotonically until a latitude of about 38°. Between latitudes 38° and 43° the variation in the predicted sea-level change is more gradual as the 1.8 mm yr^{-1} contour roughly straddles the coast. In other words, the standard model predicts that the contours of sea-level rise associated with the peripheral bulge are nearly parallel to the east coast of North America between latitudes 38° and 43°.

The predicted location of the peripheral bulge is very sensitive to changes in the lower mantle viscosity, whereas variations of the upper mantle viscosity and lithospheric thickness affect mainly the predicted amplitude of the peripheral bulge on a path traced along the North American east coast south of 45° (Fig. 4). The sensitivity of the peripheral bulge dynamics to variations in the viscosity within the mantle has previously been considered in some detail (*16*). As the deep mantle viscosity is increased the boundary between the central uplift region and the bulge migrates outward (away from) the previously glaciated region. The predicted sea-level rate near 37° (near the peripheral bulge maximum) is relatively insensitive to small changes in the peripheral bulge location, but the predicted sea-level rise in the northeastern

United States (near New Hampshire) drops significantly as the peripheral bulge migrates outward (Fig. 3B).

The predicted sea-level rates north of the peripheral bulge maximum are thus extremely sensitive to the peripheral bulge location and therefore to the value for the lower mantle viscosity used in the GIA calculations. Accordingly, we performed an inversion in which we estimated only the adjustment to the viscosity of the lower mantle and a common sea-level rate (*17*). We obtained a value for the lower mantle viscosity of $(4.7 \pm 0.3) \times 10^{21}$ Pa s , and a value of 1.4 ± 0.3 mm yr^{-1} for the common rate (*18*). Importantly, the noise in the sea-level rates corrected using the a posteriori model is a factor of ~3 smaller than that for the rates corrected using the "standard" model, although systematic variations are still visible (Fig. 5). As discussed above, the trend toward lower sea-level rates north of 38° is reduced because the migration of the "zero" contour toward the northeastern U.S., in the case of the a posteriori model, yields smaller GIA corrections in this region (Fig. 3).

The value of lower mantle viscosity we obtained is consistent with a number of recent inferences (*13*, *14*). The model, in combination with the ICE-3G deglaciation history (*6*), has been found to be consistent with a global data base of Late Pleistocene sea-level histories, and is in fact preferred over the "standard" model when only sea-level data from eastern North America are considered (*13*). Furthermore, the model satisfies the constraint on viscosity implied by the uplift decay-time estimates from southern Hudson Bay (*14*). The estimate of 1.4 ± 0.3 mm yr^{-1} for the common sea-level rise may be compared with the previously determined value of 1.9 mm yr^{-1} (*2*) for the same region. In that analysis, however, the east-coast North American sites were divided into two regions, southern and northern, with the northern yielding a sea-level rise of 1.3 mm yr^{-1}, and the southern 2.5 mm yr^{-1} (*19*). The sea-level estimates associated with other "corrected" tide gauge records in the global data set also exhibited significant scatter; it remains to be seen whether this scatter is reduced, and whether the associated estimate of sea-level rise is altered, when we use an analysis of the kind presented here (*20*).

References and Notes

1. W. R. Peltier and A. M. Tushingham, *Science* **244**, 806 (1989); W. R. Peltier and A. M. Tushingham, *J. Geophys. Res.* **96**, 6779 (1991).
2. B. C. Douglas, *J. Geophys. Res.* **96**, 6981 (1991).
3. A. S. Trupin and J. M. Wahr, in *Global Isostasy, Sea Level, and Mantle Rheology*, R. Sabadini and K. Lambeck, Eds. (Kluwer, Dordrecht, 1991), pp. 271–284.
4. GIA refers to the (ongoing) adjustment of the Earth in response to the melting of the Late Pleistocene ice sheets. The last deglaciation of the current ice age extended from approximately 20 to 5 kyr before present, and resulted in an average increase of about 120 m in the global sea-level. The adjustment phenomena is of sufficiently long time scale (several kyr or more) that, for a given location, it gives rise to an apparent secular variation in sea level.
5. All predictions of the rates of sea-level change due to GIA were based on the gravitationally a self-consistent pseudo-spectral algorithm [J. X. Mitrovica and W. R. Peltier, *J. Geophys. Res.* **96**, 20053 (1991)].
6. A. M. Tushingham and W. R. Peltier, *J. Geophys. Res.* **96**, 4497 (1991).
7. The "standard" Earth model is defined by an inviscid core, an elastic lithosphere of thickness 120 km, an upper mantle viscosity of 10^{21} Pa s, and a lower mantle viscosity of 2×10^{21} Pa s. The elastic structure is given by the seismically determined Preliminary Reference Earth Model [A. M. Dziewonski and D. L. Anderson, *Phys. Earth Planet. Inter.* **25**, 297 (1981)] and the upper/lower mantle boundary is

taken to occur at a depth of 670 km. The label "standard" is not meant to imply a community consensus on this model; rather, it emphasizes that the model is the primary one which has been used to correct tide gauge records for the influence of GIA and to determine global rates of sea-level rise from the residual records.

8. J. L. Davis, J. X. Mitrovica, H.-G. Scherneck, N. W. Casey-McCabe, in preparation. The sea-level observation $L_i(t_j)$ for the ith site and for the epoch t_j is modeled as:

$$L_i(t_j) = a_i + r_i(t_j - t_\circ) + b_j$$

where a_i is a site-dependent offset, r_i is a site dependent sea-level rate, $t_\circ$ is a reference epoch, and b_j is an epoch dependent offset which represents the correlated interannual variations. The a_i, r_i, and b_j are all estimated simultaneously. The problem as stated is underdetermined, and so constraints are required on the average value of the b_j and their slope.

9. The tide gauge data were obtained from the Permanent Service for Mean Sea Level (PSMSL) at the Bidston Observatory, Birkenhead, Merseyside, England. Annual means were used.

10. The mathematical model (*8*) assumes that the interannual variations of sea-level for different sites are highly correlated. To study these correlations, straight line fits were first independently performed to the data (*9*) from all sites represented in the PSMSL data base on the east coast of North America north and inclusive of Key West, Florida, and south and inclusive of Halifax, Nova Scotia. The residuals to the best fit straight line were then correlated with those of the New York site,

which is centrally located and has a long series of observations. If the correlation of these residuals was 0.4 or greater, and the site had 20 or more (not necessarily consecutive) epochs in common with the New York data set, then the site was used in the ensuing analysis. All the sea-level rates were simultaneously used to determine the parameters a_i, r_i, and b_j (*8*). The combined data set, after editing, yielded 1851 data which were used to determine 172 parameters. The overall RMS fit was 17 mm. The RMS variation of the b_j, which is an indication of the scatter "absorbed" by the interannual variations, was 21 mm. The rate for the Richmond site was highly anomalous, possibly because of its location on a river well inland, and was not used in the subsequent analysis

11. J. L. Davis and J. X. Mitrovica, in preparation.
12. M. Nakada, and K. Lambeck, *Geophys. J. Int.* **96**, 497 (1989); K. Lambeck, P. Johnston and M. Nakada, *Geophys. J. Int.* **103**, 451 (1991); W. Fjeldskaar and L. Cathles, in *Global Isostasy, Sea Level, and Mantle Rheology*, R. Sabadini and K. Lambeck, Eds. (Kluwer, Dordrecht, 1991), pp. 271–284.
13. A. M. Tushingham and W. R. Peltier, *J. Geophys. Res.* **97**, 3285 (1992).
14. J. X. Mitrovica and W. R. Peltier, *Geophys. J. Int.* in press (1995).
15. In these areas the sea-level signature is dominated by the deformation of the solid surface rather than by undulations of the ocean surface. Hence, the sea-level fall in Canada is a manifestation of the uplift of the depressed solid surface in that region, while the sea-level rise is associated with the subsidence of the peripheral bulge which surrounds the central depression.

16. J. X. Mitrovica, J. L. Davis, I. I. Shapiro, *J. Geophys. Res.* **99**, 7075 (1994).

17. The least-squares solutions used the tide gauge rates determined from the earlier analysis as observations. The full covariance matrix from that solution was also used. A constant offset, representing the common sea-level rate, was simultaneously estimated. The χ^2 for the 36 data and two parameters from the solution was 130.7. The χ^2 when an offset only was estimated was 487.1. Thus, a decrease of a factor of $\sim$3 occurred for one fewer degree of freedom.

18. The uncertainties given throughout are the formal standard deviations scaled by the square-root of the χ^2 per degree-of-freedom.

19. The new predictions also bring into accordance the sea-level rate at Key West (latitude 25°). The sea-level record for this site extends back to 1846, although the PSMSL data for this site begin in 1913 [G. A. Maul and D. M. Martin, *Geophys. Res. Lett.* **20**, 1955 (1993)].

20. Furthermore, there is room for improvement in the technique we have used to determine model corrections. We have not yet performed a resolving power analysis, for example, to determine at which depths in the lower mantle we are most sensitive. Our future analyses will investigate a number of affects including potentially important uncertainties in the ice model. In the future, too, Global Positioning System data will be used to measure the three-dimensional deformation of the land.

21. N. W. Casey McCabe assisted in the analysis of tide gauge data. P. Elósegui and I. Shapiro provided useful comments on the manuscript. This work was supported by NASA grant NAG5-1930 and by the Smithsonian Institution.

Figure Captions

Fig. 1. Location of the east-coast North American tide-gauge sites used in the present analysis.

Fig. 2. (**A**) "Raw" sea-level rates from the east coast of North America, from a previous analysis (*2*). Only sites with a largely complete record during the years 1930–1980 were used. (**B**) After correction for GIA using the standard model, these rates still exhibited a significant variation which in the earlier analysis was interpreted as a "step" at a latitude of about 38°. (**C**) A recently developed method for tide gauge analysis (*10*) enables shorter sea-level records to be utilized, providing for a better geographic distribution of the "raw" rates to be obtained. (**D**) The step appears as a continuous variation in the new set of rates corrected for GIA using the standard model. The points indicated by squares in (A) and (B) were not used in the earlier analysis because the rates were considered to differ too much from those from surrounding sites. However, our analysis suggests that these differences may simply be part of the now-apparent continuous variation.

Fig. 3. Numerical predictions of the present day rate of change of sea level in the eastern United States due to glacial isostatic adjustment. The predictions were calculated (*5*) using the ICE-3G deglaciation chronology (*6*) and (**A**) the standard Earth model (*7*) and (**B**) the same model as (A), except the lower mantle viscosity has been increased to 4.7×10^{21} Pa s.

Fig. 4. Numerical predictions of the present day rate of change of sea level on a profile taken along the the east coast of North America. The predictions were calculated (*5*) using the ICE-3G deglaciation chronology (*6*) and a suite of Earth models in which the lithospheric thickness, upper mantle viscosity and lower mantle viscosity, were varied from the value which characterizes the "standard" Earth model (*7*). (**A**) Lower mantle viscosities 10^{21} Pa s (dashed), 2×10^{21} Pa s (solid), 3×10^{21} Pa s (dotted), and 5×10^{21} Pa s (dashed-dotted). (**B**) Upper mantle viscosities 10^{21} Pa s (solid), 7.5×10^{20} Pa s (dashed), 5.0×10^{20} Pa s (dotted), and 3.0×10^{20} Pa s (dashed-dotted). (**C**) Lithospheric thicknesses 95 km (dashed), 120 km (solid), 195 km (dotted), and 245 km (dashed-dotted). Others have suggested that an increase in the lithospheric thickness might be appropriate for this region (*13*) and might account for the anomalous sea-level trends from North America (*3*) . However, the comparison of (A) and (C) illustrates the quite different effects of changing these parameters. Using the tide gauge data themselves to estimate corrections to the Earth-model parameters leads to a doubling of lower mantle viscosity, and only small changes to the other parameters.

Fig. 5. Results from the new analysis of tide gauge data. (**A**) Raw tide gauge rates (as in Fig. 1D), as well as the glacial isostatic adjustment correction, shifted for the best-fitting coherent rate computed for the a posteriori model (dotted line), which is characterized by a lower mantle viscosity of 4.7×10^{21} Pa s. The predicted corrections for the standard model are shown by the dashed line. (**B**) The tide gauge rates corrected using the a posteriori model show much less variation than previously. The dashed line represents the estimated common sea-level rise of 1.4 mm yr^{-1}.